An Aeronautical Mobile Terminal for High Data Rate 20/30 GHz Satcom

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Abstract -- This paper discusses the Jet Propulsion Laboratory's (JPL's) Broadband Aeronautical Terminal (BAT), an experimental aeronautical mobile, **high data rate, 20/30 GHz satellite communications (satcom) terminal, that will be evaluated in-flight on several different aircraft. The BAT will communicate via NASA's Advanced Communications Technology Satellite (ACTS) and will investigate the efficacy of 20/30 GHz aeronautical mobile satcom (aero-satcom). As a flying digital communications laboratory, its use will provide the systems and technology groundwork for an eventual commercial 20/30 GHz aero-satcom system. The benefits of 20/30 GHz aero-satcom, as compared to lower frequency bands, include an abundant frequency allocation amenable to higher bandwidth applications and smaller antennas. This paper presents a brief history of the events leading to the BAT in the introduction, followed by discussions of the flight experiment plans, the communications** link budgets, and the individual **BAT subsystems.**

I. INTRODUCTION

A. 1980's: *UHF& L-band*

In the early 1980's JPL asserted a vision of personal mobile satcom. NASA tasked JPL as the lead NASA center for mobile satcom to develop the enabling technologies and transfer that technology to industry, so as to accelerate the introduction of a U.S. Mobile Satellite Service (MSS) commercial industry. Industry technology transfer is one of NASA's formal missions. JPL commenced its Mobile Satellite Experiment (MSAT-X) task, and throughout the 1980s developed the plans for and demonstrated the potential of mobile satcom. JPL conducted system studies of the space and ground segments, studied the propagation effects of the mobile channel, identified key system and subsystem functions, established subsystem requirements, developed hardware, integrated complete mobile experimental systems and conducted system field trials [1- 12]. The first MSAT-X system studies addressed the original FCC proposal for a UHF frequency allocation for mobile satcom. The FCC later adopted an L-band allocation instead because of the significant reduction in antenna size afforded by the higher frequency, and the additional bandwidth available at L-band. JPL's MSAT-X developments include low profile, medium-gain satellite-tracking antennas (both phased array and mechanically steered) [13-21] and robust modulation and coding schemes [22-29]. JPL conducted field trials using the complete systems developed by the MSAT-X task. Several land-mobile field trials were conducted from 1986.1989, evaluating L-band digital voice communications from a car or van using geostationary satellites of opportunity [30-34]. An aeronautical experiment was conducted in partnership with the Federal Aviation Administration in 1989, demonstrating L-band 4.8 Kbps digitally compressed voice communications via an Inmarsat satellite stationed over the Atlantic, with a B727 flying across the Northeastern U.S. [35]. By the late 1980s L-band personal mobile satcom had taken off commercially. In 1989 the American Mobile Satellite Corporation (AMSC) was licensed by the Federal Communications Commission (FCC) to develop a U.S. MSS. Since 1991 Inmarsat has provided a single channel voice, data, or FAX link at 9.6 Kbps available to aeronautical users at L-band. AMSC may provide similar services as well. Furthermore, both Inmarsat and AMSC may offer multiple voice and data channel services soon. These developments confirmed the reality of JPL's vision of personal mobile satcom.

As L-band aero-satcom systems are implemented and their benefits are realized, it is likely that the communication role envisaged for aero-satcom will grow. Concepts such as providing passengers with an "office in the sky," or real-time news and sports broadcast will expand. Increased demand for the potpourri of service offerings foreseen for the future of aero-satcom, which will continue to require increased bandwidth, is likely to motivate a need for more spectrum than is available at L-band. K/Ka-band satcom could provide these new high data rate services in addition to enhancing the capabilities available at L-band as the demand for these services increase.

B. 1990's: K/Ka-band

K/Ka-band has some of the same benefits over L-band as L-band dots over UHF reduced antenna size, increased antenna gain and bandwidth, and more real estate (FCC allocated spectrum), all of which afford higher bandwidth applications such as video teleconferencing. The reduced drag of smaller K/Ka-band antennas (due to the increased frequency), and the large amount of available bandwidth makes the development of a K/Ka-band aero-satcom system a logical choice to support the growth of such services. In the late 1980's JPL began detailed studies of the use of Ka-band for personal mobile satcom [36-41], and along came a Ka-band satellite of opportunity.

In 1990 JPL developed an opportunity to propose using the NASA ACTS satellite for mobile Ka-band satcom. ACTS had not been designed for mobile satcom, but JPL set out to show that it could be used to demonstrate a wide variety of mobile communication services. Since 1990 JPL has focused its mobile satcom efforts on K/Ka-band and NASA's ACTS satellite, with a series of tasks that constitute JPL's ACTS Experiments Program. The vision of this program is to enable the next generation of mobile satcom technology and services, including land mobile, aeronautical mobile, maritime mobile, and hand-held satcom at 20/30 GHz. The new program's mission is the same as that of the MSAT-X program: to develop the enabling technologies and transfer that technology to industry.

ACTS Mobile Terminal (AMT): The AMT task addressed the land mobile segment of JPL's ACTS Experiments Program. As soon as ACTS became operational JPL demonstrated its use for land mobile satcom with the AMT, a 20/30 GHz land-mobile satcom terminal developed in two years and installed in various vehicles [42-43]. Installed in a satellite news gathering van the AMT has demonstrated a variety of communication services (up to 64 Kbps), such as digitally encoded voice, compressed video and data file transfers, while traveling on highways, urban and rural roads. Installed in a U.S. Army High Mobility Military Wheeled Vehicle (HMMWV), the AMT has demonstrated mobile video teleconferencing to several U.S. Army Generals, video conferencing with other officers at remote sites, while riding in the passenger seat. Two U.S. patents have come from the AMT effort, covering the antennas and antenna tracking scheme [44-46]. Following the success of the land mobile AMT. attention shifted to aeronautical mobile satcom.

Broadband Aeronautical Terminal (BAT): The BAT task addresses the aeronautical segment of JPL's ACTS Experiments program. The BAT is a mobile, digital communications terminal being developed by JPL for NASA in an effort to advance the technology and system concepts necessary for a future commercial 20/30 GHz aero-satcom system [47-48]. The BAT system is broadband in the sense that it will provide communication rates that greatly exceed that typical of current airline phone/fax services. The BAT will demonstrate data rates of 384 Kbps and higher. To support such high data rate communications the BAT will incorporate a high gain antenna with a very abundant bandwidth of approximately 1 GHz (matching the entire ACTS bandwidth) and a two-axis mechanical pointing system to track the satellite while the aircraft flies about. With many high band width services to chose from, the BAT is designed primarily to demonstrate video communications, since video is attractive, and with recent strides being made in compression algorithms and microprocessor speed, new complex video compression techniques have recently significantly improved the video quality that can be conveyed within a limited bandwidth, One of the first commercial applications of 20/30 GHz aero-satcom may become live video in the passenger cabin, which could, for the entertained (or teleconferencing) passenger, seemingly shorten travel time significantly. Alternately, large amounts of information could be conveyed to the cockpit and reduced into a graphical format that is easily interpreted by the pilot, such as three-dimensional weather maps. These possibilities will be evaluated with the BAT. The current state of the BAT task is presented in this paper. The flight experiment plans, the system link budgets and the individual BAT subsystems are discussed.

II. SATCOM SYSTEM DESCRIPTION

A. System Configuration

The system configuration for the BAT experiments consists of a fried (ground-based) terminal, ACTS in geostationary orbit, and the BAT in an aircraft, as shown in Figure 1. In the forward link (fixed station-to-aircraft) the JPL fixed terminal will send communications data and a pilot tone (for antenna tracking) via ACTS to the aircraft terminal. In the return link (aircraft-to-fixed station) the aircraft will send communications data via ACTS back to the fixed ground station at JPL. The BAT antenna has circular polarization so that polarization mismatch doesn't vary significantly with changes in polarization alignment. (ACTS -- not designed for mobile applications -- has linear polarization.) This imposes a polarization mismatch that only varies by the amount of the axial ratio of the BAT antenna (about 2 dB) as a function of polarization alignment, with an "average" polarization mismatch of about 3 dB. Changes in polarization alignment are caused by operation in different geographical locations as well as changes in aircraft orientation during flight.

B. The ACTS Satellite

Via NASA's ACTS satellite, at 100 deg West longitude, flight experiments may be conducted while the aircraft flies anywhere that a line-of-sight view of ACTS is available, from Hawaii to Alaska to Greenland to Antarctica, using ACTS' mechanically steered spot beam. Figure 2 is a world map of the local ACTS elevation look angle, showing the boundary of just where such a line of sight is available. ACTS will be used in its Microwave Switch Matrix (bent pipe) mode for the BAT experiments, with its mechanically steered spot beam "piped" together with the Los Angeles spot beam (JPL ground station). The entire set of ACTS spot beams are diagramed *in* Figure 3, showing everywhere that the fixed station may be located. The ACTS steerable spot beam must track the aircraft by continuously following the aircraft's reported location, reported by a GPS system on the aircraft via an auxiliary data channel through the main communications link. The ACTS steerable beam pointing must be updated at least once every four minutes to keep the aircraft within the -0.5 dB contour of the ACTS beam A "fixed" spot beam will be used for the communication with the fixed ground terminal at JPL (the other end of the satcom link), Two transponders will be used on ACTS for these experiments. One transponder will be configured to support the forward link (from the JPL fixed station to ACTS through the 30 GHz Los Angeles spot beam, then relayed by ACTS to the BAT in the aircraft via the 20 GHz steerable beam trained on the aircraft) and another transponder configured to support the return link (from the aircraft to ACTS, through the 30 GHz steerable beam trained on the aircraft, then relayed by ACTS to the JPL fixed station via the 20 GHz Los Angeles spot beam). The ACTS uplink is 28.9-30.0 GHz (Ka band), linearly polarized, and its downlink is 19.2-20.2 GHz (K band), linearly polarized, orthogonal to the uplink in each respective spot beam.

C. System Link Budgets

The baseline forward link (data and pilot signals sent to aircraft from JPL via ACTS) and return link (data signal only returned from aircraft to JPL via ACTS) link budgets for the experiment are presented in Tables 1-3. The forward link is identical for both experiments currently planned (one with NASA Ames and another with Rockwell Collins), and is summarized in Table 1. The return link is of a different data rate for the Ames and Rockwell experiments: Table 2 presents the Ames experiment return link, and Table 3 the Rockwell experiment return link.

In every case the ACTS steerable beam will link the aircraft and ACTS, and the Los Angeles Spot beam will link the JPL fixed station to ACTS. This represents a particular configuration of the ACTS Matrix Switch Mode, with the Los Angeles spot beam "piped" to the steerable beam, and including the need to continuously report the true position of the aircraft to the ACTS Control

Facility so the steerable beam may be kept pointing at the aircraft.

111. FLIGHT EXPERIMENT PLANS

Flight experiments are planned to evaluate and demonstrate duplex video communications between the BAT in flight and a fixed ground station at JPL. The experiments are scheduled to commence in late 1995.

A. JPL Objectives

JPL's objectives for the BAT experiments are: (1) to evaluate the performance of high data rate communications in the 20/30 GHz aero-satcom environment, including full-duplex digital compressed video, (2) to characterize the propagation effects of the 20/30 GHz aero-satcom channel, throughout take-off, cruise, and landing, and (3) to determine the systems groundwork necessary for an eventual commercial K/Ka-band aero-satcom system. The system performance will be evaluated both quantitatively and qualitatively. Qualitatively, the principle criterion will be the ability to maintain a full-duplex video link during flight, including take-off and landing. Quantitatively, the link performance is a direct function of the bit error rate (BER). The BER in turn is a function of the signal to noise ratio, Doppler, etc. Measurements will be made to characterize the propagation effects. An attempt will be made to identify and separate the sources of channel degradation (cloud and rain effects, multipath, etc.). Cumulative fade distributions will be computed for the channel conditions encountered. The quantitative assessment will include a comparison between theoretical and experimental results. From the data collected during the experiments, and the ensuing analyses, recommendations about the design of a practical and cost effective commercial 20/30 GHz aero-satcom system will be made and published in the literature.

B. Industry and Government Partnerships

JPL has sought and obtained industry and government partnerships to help support the flight experiments primarily by providing the aircraft in which to install the BAT. Currently two partnerships have been established: one with Rockwell International Corp., Collins Avionics & Communications Division (Rockwell Collins), and another with NASA's Ames Research Center (ARC). Rockwell Collins has provided a Sabreliner 50 eight-seat business jet, and ARC has provided a Lockheed C-141 large converted military cargo jet, Each partnership supports a unique experiment objective.

NASA Ames Research Center (ARC) Partnership: ARC has made available a Lockheed C-14 1 cargo jet, dedicated to airborne astronomy with an infrared telescope, in which the BAT will be installed and flown as part of an educational experiment. ARC has dedicated this aircraft to high-altitude airborne infrared astronomy since the 1970's and has named the aircraft the Kuiper Airborne Observatory (KAO). A live video link with the KAO in flight will enable groups of elementary and secondary school students to remotely participate, in their classroom, with their science instructor who may accompany, in flight, the scientists who operate the infrared telescope. The activities of this both scientific and educational experiment are planned to be broadcast live on Public Broadcast System (PBS) television stations nation wide, with the program entitled, "Live from the Stratosphere." The students will observe the telescope images immediately in their classroom and will be given the opportunity to control the telescope from the classroom and select different star fields to observe.. In addition to the live classroom television feed, the BAT aero-satcom link will be connected to the Internet to allow a larger number of students to participate in these experiments over the Internet computer network. The ARC objective for the experiment is to successfully utilize the KAO with the BAT satcom link to provide an exciting science experience for elementary and secondary school students and thereby possibly encourage greater interest in the field of science.

The KAO is a National Facility operated and maintained by NASA to support scientific research in infrared astronomy, and is based at the Ames Research Center, Moffctt Field, Calif. The KAO C-141 aircraft has been specially modified to contain a 91 cm infrared (IR) telescope for performing astronomical observations at altitudes up to 45,000 ft. This altitude permits instruments to observe objects in the JR region of the electromagnetic spectrum while minimizing IR absorption by the Earth's atmosphere. Scientists from all over the world have used this flying observatory for twenty years. Real-time communications with the KAO will be provided by a radio link through NASA's ACTS satellite, using both airborne and ground-based communication terminals developed by JPL for the BAT task.

Rockwell Collins Partnership: Rockwell Collins has made available a Sabreliner 50 business jet in which to fly the BAT. Rockwell Collins proposes an experiment for which video teleconferencing is conducted while evaluating a technique for autonomously controlling the ACTS steerable beam. The position of the aircraft is continuously observed by a Rockwell Global Positioning System (GPS) receiver in the aircraft, The aircraft position reports are relayed to the ACTS master control station via a data stream embedded in the return video link from the aircraft. The ACTS steerable beam tracks the aircraft using the periodic aircraft position reports, unleashing the aircraft from having to follow a preset flight path to remain within the footprint of the steerable beam.

C. Aircraft Installation

The BAT will be installed in the aircraft as generally depicted by the sketch in Figure 4. The antenna will be installed near the top center of the fuselage, and all other BAT equipment will be mounted in an equipment rack in the cabin, near the antenna to minimize cable length and RF loss. The BAT will be a turn-key system, so user interaction will only be required during initial setup of the experiments. The user interface is a video display or computer workstation, along with a video camera, which may be located in the cabin some distance away from the BAT equipment rack. Current commercial jumbo-jet installations can require that the electronics mount in an electronics bay (E-bay) which is already crowded with other communication equipment. This requires that any new communications electronics be highly integrated and compatible with other existing systems in order to minimize the additional space required. Figure 5 shows an antenna similar in size to the BAT antenna (but providing data rates much lower than the BAT) installed on a Boeing 737.

An air worthiness approval review is typically required prior to the installation of the equipment in the aircraft, At such a review, analyses of the distribution of the additional aerodynamic and structural loads and of the affects on flight stability are addressed, The aerodynamic drag loads caused by a protruding antenna radome must be quantified by analysis. The analysis may reveal flight envelope restrictions due to unstable airflow over the airfoils behind the protruding radome. The radome analysis also determines the distribution of dynamic pressures about the radome, which must be accounted for in the mechanical design of the radome. Analysis of the installation must demonstrate that the fuselage can withstand the additional loads of the antenna mass and radome drag loads under the most severe flight and vibration conditions expected. Such analyses must be done separately for each unique installation.

Any aircraft installation, as well as the equipment design, must adhere to the aircraft industry standard practices documented in the ARINC and RTCA-DO specifications. Some examples of these standards are: 1) RTCA-DO-160 specifies "Environmental Conditions and Test Procedures for Airborne Equipment," (including many environmental factors such as vibration loads for various types of aircraft, for equipment mounted either directly to the fuselage or rack mounted in the cabin), 2) RTCA-DO-21O specifics "Minimum Operational Performance Standar ds for Aeronautical Mobile Satellite Services (AMSS)," 3) ARINC-741 specifics an Aviation Satellite Communication System (system design and aircraft installation provisions). 4) ARINC-429 specifies the Mark 33 Digital Information Transfer System (a data bus from which aircraft navigational pitch/yaw/roll information may typically be obtained). ARINC documents may be obtained by contacting Aeronautical Radio, Inc., ARINC Document Section, MIS 5-123, 2.551 Riva Road, Annapolis, MD 21401-7465 USA (410) 266-4117. RTCA documents may be obtained by contacting RTCA, Inc., 1140 Connecticut Avenue, N. W., Suite 1020, Washington, D. C. 20036 USA 202-833-9339,

IV. Broadband Aeronautical Terminal (BAT) Subsystems

The BAT consists of the subsystems depicted in the block diagram of Figure 6. These include an antenna system, RF and IF converters, modem, video codec and data acquisition system. These subsystems are discussed below.

A. Antenna and Controller

The BAT requires the custom development of a two-axis, high-gain antenna system to accommodate the satellite tracking requirements imposed by aircraft flight and the high data rate communications. JPL elected to contract out the antenna development, in line with NASA's mission of transferring technology to and developing partnerships with U.S. industry. EMS Technologies Inc. won the competitive bid for the contract in early 1994. The antenna tracks the satellite continuously in azimuth angle, and over the range of elevation angle of 5 deg below the aircraft horizon to zenith. This hemispherical coverage allows for typical aircraft banking while maintaining communications over a large portion of the Earth where ACTS is visible. The antenna RF requirements include that it maintain, in flight, a minimum transmit gain of 29 dB and a minimum receive sensitivity of O dB/K G/T (ratio of isotropic receive gain to receive system noise temperature), with circular polarization and axial ratio no greater than 3 dB. The antenna provides a maximum of 49 dBW EIRP uplink to the satellite (with a maximum of 120 W RF power input to the antenna).

The aeronautical antenna system consists of three assemblies: a main antenna assembly (MAA), its radome cover, and an antenna controller. The MAA contains the antenna mechanism and radiating apertures, mounts externally to the fuselage, and fits under the radome. The antenna controller controls the antenna mechanism and is rack-mounted inside the cabin.

The MAA incorporates separate transmit and receive arrays. Both arrays are flat plate slotted waveguide arrays with uniformly illuminated aperture, each having several hundred radiating slot elements. The arrays are mounted adjacently on the two-axis antenna positioner. Circular polarization (CP) is achieved with a meanderline polarizers placed on the face of each array. Figure 7 shows a sketch of the antenna and its radome cover. The MAA will employ an elevation-over-azimuth positioner. It is allocated a weight budget of 60 pounds and is constrained to fit under a radome with protrusion less than 7 inches. The axis of elevation angle rotation is significantly offset from the azimuth axis to reduce radome height while allowing space for the azimuth positioner mechanism. The staircase trimming of the upper, outside corners of the arrays allows for a more gradually curved radome. Figure 8 shows the measured transmit beam far-field patterns in a three dimensional perspective view. The transmit array is designed for a 4% bandwidth centered at 29.45 GHz. The transmit beam half-power beamwidths are 2.5 and 5 deg. in cross-elevation and elevation, respectively. The receive beam is very similar in shape to that of the transmit beam, only with a wider beamwidth. The receive array is designed for a 5% bandwidth centered at 19.7 GHz. The receive beam half-power beamwidths are 4 and 7 deg, in cross-elevation and elevation, respectively. The required sidelobe levels are less than 10 dB below the beam peak for both transmit and receive beams. The combined width of the two apertures is less than 16 inches. Their height is less than 4.5 inches. Other than each array's trimmed comer, the aperture dimensions are 8.1 x 4.2 inches (transmit) and 7.5 x 4.4 (receive). The 5% bandwidth is achieved with a hybrid series/parallel array feed design with the quality factor of each slot optimized for the bandwidth.

The antenna is covered by a multilayer radome with a hemi-ellipsoidal shape. The radome requirements provided a challenging RF design problem. The axisymmetric radome must be less than 7 inches high and 28 inches maximum diameter. A circularly symmetric radome design was chosen to simplify the electromagnetic analysis of the antenna since earlier aerodynamic analysis determined that it would not adversely affect the flight stability of the C-141 or Sabreliner. The high aerodynamic loads expected require that the radome be sturdy, and as a result somewhat thick and bulky. Since the receive and transmit apertures are offset significantly from the radome center, the shallow radome height, combined with the full hemispherical coverage results in a range of incidence angles of O to 70 degrees between the antenna beams and the face of the radome. In addition, the radome must be electrically tuned over two frequency bands and also provide low axial ratio. The baseline design is a multi-layer design with three layers of dielectric and two honeycomb layers. This design results in predicted loss of less than 0.4 dB over the range of incidence angles expected. The overall radome weight, including mounting hardware is 14 lb. The radome will have an exterior coat of hydrophobic material to minimize the signal attenuation effects of rain that could otherwise wet the exterior radome surface and degrade the RF signals.

The antenna controller must keep the antenna pointed at the geostationary satellite as the aircraft maneuvers during flight, after first acquiring the satellite signal. The acquisition procedure starts with pointing the antenna to the point in space where the satellite is expected, using the aircraft orientation information supplied by the aircraft navigation system and knowing the satellite orbital location. A tine-search is then conducted to verify the actual signal direction. After acquisition is completed the tracking algorithm takes over. Tracking essentially requires that the antenna is inertially stabilized -- recall that ACTS is geostationary, and a point on the Earth is essentially inertially stable, at least on the short term of a few minutes. The allowance, in the link budget, for antenna tracking error is only 0.5 dB, which given the relatively high directivity of the antenna, translates into an allowable pointing error of only a few tenths of a degree. It accomplishes this tracking function with the use of three sources of pointing information. The primary source of pointing information is an inertial sensor, or Inertial Reference Package (IRP) with a integrated temperature sensor. The IRP uses three orthogonal miniature vibrating quartz gyros to measure angular rates of aircraft pitch, yaw and roll. Temperature bias and installation misalignment are removed, and the result integrated to produce an estimated inertial space vector reference. This is then used as the primary reference against which the antenna is stabilized, The long-term drift and non-linearities of the inertial sensor prevent it from being used as the only source for pointing information. Any change in aircraft orientation, as reported by the IRP, is immediately counteracted by the antenna controller. A secondary source of inertial tracking information is the Inertial Navigation System (INS) subsystem in the cockpit, which is primarily relied on for initial acquisition but not so much during tracking once the signal is acquired, The aircraft INS information is a secondary tracking source because it is typically not provided fast enough by the aircraft navigation bus (ARINC 429) for precision antenna tracking, and the fuselage may bend or twist just enough during flight (due to turbulence) to make the INS data unsuitable for antenna tracking, The small amount of fuselage bending and twisting is enough to discount the INS information because the antenna beam is very narrow, and the INS reports the orientation of the cockpit, not the location where the antenna is installed. Only the Iong-term trend of the difference between the INS data and the IRP is ohserved, so as to average out the fuselage bending effects. The third source of pointing information is feedback to correct any long-term residual pointing error that may accumulate in the IRP. To provide the feedback, the antenna controller monitors the signal strength of an analog, coherently detected, CW pilot signal relayed by the satellite, and received through the antenna. To estimate pointing error the antenna is intentionally scanned through a small circle (about 0.1 deg radius) in inertial space about the current estimate of the satellite direction vector. The estimate of actual pointing error is a low-bandwidth source of feedback (one estimate only every 4 seconds or so) which is sufficient to correct the errors which accumulate in the IRP inertial sensors. This feedback-corrected inertial stabilization technique functions welt, and with only a sub-Hertz feedback bandwidth because the inertial sensor errors are small and slowly varying.

'l'he receive front-end low noise amplifier (LNA) is integral to the MAA so that the receive system noise figure is not significantly degraded by the cabling losses between the antenna and RF/IF Converters. A 20 GHz noise figure of 2.5 dB is anticipated with a gain of 32 dB for the LNA. In order to avoid system receiver desensitization when transmitting, the LNA gain and noise figure are required to not degrade significantly with the injection (leakage) of a 30 GHz signal simultaneous with the presence of the 20 G] Iz receive' signal, To prohibit such desensitization a receive passband filter is placed at the LNA input.

B. RF &IF Conversers

'l'he RF/IF Converters provide frequency and power conversion between the antenna and the modem. Doppler tracking/precompensation is also provided at this stage. The RF and IF Converters respectively provide unique functions which are described below.

The RF Converter provides frequency and power conversion between the antenna and the IF Converter. Its upconverter and downconverter functions are descrihcd separately below. A Traveling Wave Tube Amplifier (TWTA) is a component of the upconverter stage of the RF

Converter. A different TWTA is used in the ARC C-141 aircraft (100 W) than in the Rockwell Collins Sabreliner (40 W), since the Sabreliner doesn't have enough generator power for the larger TWT'A. A block diagram of the entire RF Converter is provided in Figure 9.

The RF Converter provides frequency and power upconversion between the IF Converter (3.373 +/- 0.15 GHz) and the transmit antenna (29.634 +/- 0.15 GHz). The frequency conversion is accomplished with a harmonically pumped mixer with a local oscillator (LO) of 13.1305 GHz, which is internally multiplied by a factor of two to 26.261 GHz. The multiplied LO signat is mixed with the IF signal, and the upper sideband component is selected by a bandpass filter. The power conversion, prior to the TWTA, is accomplished with two stages of amplification, one at the IF and one at the Ka-band RF output. Gain control is provided by a PIN diode voltage-controlled attenuator at the input of the upconverter. The TWTA for the C-141 aircraft provides up to 100 W 30 GHz RF power (at the TWTA output), while requiring as much as 1 KW from its power supply. A 15 foot waveguide cable between the TWTA and antenna presents an RF loss of nearly 4 dB, and thereby the maximum RF power level at the antenna is about 40 W. In the Sabreliner installation, with the same 4 dB cable loss, about 17 W 30 GHz RF power is delivered to the antenna while its TWTA requires about 500 W power supply.

The RF Converter provides frequency and power conversion between the receive antenna (19.914 +/- 0.15 GHz) and the IF Converter (3.373 +/- 0.15 GHz). The frequency conversion is accomplished with a balanced mixer. The LO signal is mixed with the receive signal, and the lower sideband component is selected with a bandpass filter. The power conversion is accomplished with two stages of signal amplification, one low noise amplifier at the K-band input and one S-band amplifier at the IF frequency. A preselect filter provides spurious rejection at the input, prior to signal amplification. A manually controlled step attenuator on the front panel controls the dynamic range variations in receive power so the IF Converter receives the proper noise power level from the RF Converter. The downconverter is characterized by a noise figure of 10 +/- 1 dB and a gain of 20 +/- 1 dB.

The IF Converter provides frequency and power conversion between the Modem (70 MHz) and the RF Converter (3.373 GHz). It is the IF Converter that accomplishes the frequency channel selection. It provides 6000 frequency tuning steps, via front panel thumbwheel control, with a step size of 50 KHz. It provides phase-locked loop (PLL) Doppler tracking (+/- 31 KHz) of the pilot signal, and also transmit data signal Doppler pre-compensation, accomplished by shifting the transmit frequency by a scaled replica of the Doppler received in the forward link. Precompensation is necessary in a multi-user system to confine the return link signal for each user to a specific channel bandwidth that is not spread by the Doppler (to keep from reducing the system bandwidth efficiency). With a maximum aircraft ground speed of 700 MPH (including tail wind) the maximum Doppler is about 31 KHz at 30 GHz, and 21 KHz at 20 KHz. The PLL coherently detected pilot signal is also supplied by the IF Converter to the antenna controller to aid the antenna tracking function.

A block diagram of the IF Converter is provided in Figure 10. The downconverter 3.373 GHz input (on the middle. right hand side of the diagram) is split to both the pilot tracking loop (bottom of diagram) and the Modem (data channel) output path. (The pilot and data signals are distinguished by different frequencies, but both are contained within the same +/- 150 MHz system tuning bandwidth.) The pilot tracking loop phase-tracks the pilot signal with a PLL. The PLL in-phase (Pilot I) signal is supplied to the antenna controller for antenna tracking. The PLL detected pilot signal frequency (Doppler) is then mixed with the Modem data channel signal (after pre-mixing with the tuner synthesizer LO at the top center of the diagram) to track out the Doppler in the data signal and produce the final 70 MHz Modem IF (pilot tracking loop). Finally the PLL detected pilot signal frequency (Doppler) is scaled in frequency by 3/2 (at the very bottom of the diagram) and used to pre-compensate the return transmit link for the Doppler expected in the return link (top left of diagram), so that the signal frequency received at the fixed station on the return link has only a residual Doppler shift.

C. Modem

The modem was commercially procured. Two of the factors that helped to narrow down the procurement choices were the need for rapid re-acquisition following a loss of signal, and the ability to maintain simultaneously different dots rates for both links (forward and reverse directions). The unit selected takes typically less than 3 sec to rapid restart, including the video codec re-acquire period also. The unit has four auxiliary data ports that may be used.

The modem translates the 70 MHz signal from the IF Converter to a digital baseband signal, and vice versa. It uses coherent BPSK with concatenated coding and interleaving between the two codes. The inner code is a convolutional code, and the outer code Read-Solomon. The modem operates at data rates from 9.6 Kbps to 2 Mbps. A nominal data rate of 384 Kbps (bi-directional) is planned for the KAO experiment, and for the Rockwell experiment a special feature of the modem to operate with different data rates in each direction will be used to obtain 384 Kbps in the forward link but only 112 Kbps in the return link (because the Sabreliner doesn't have enough electrical power to afford operating the larger TWTA at it full output power level). A modem bit error rate performance of 10^{-6} is required for proper video codec operat ion, and this requires an Eb/No (signal energy to noise spectral density level) of 4 dB, including 1 dB of loss with respect to theoretical.

D. Video Codec

The video coder/decoder (codec) was commercially procured. It is a unit typically used for teleconference sessions. A standard H.261 video compression algorithm is used with proprietary pre- and post-processing to improve the performance in regard to factors such as rapid re acquisition. It provides a number of voice compression algorithms to choose from. Significant factors which helped narrow down the choices for the procurement were: cost, a wide range of data rates, different data rates simultaneously for the two directions, and standard auxiliary data ports independent of the video but with autonomous mux-ing into the (video) data stream. It translates between the NTSC video signal and the digital communication link. It will operate at data rates from 56 Kbps to 2 Mbps. A nominal data rate of 384 Kbps (bi-directional) is planned for the KAO experiment, and for the Rockwell experiment a special feature of the modem/codec to operate with different data rates in each direction will be used to obtain 384 Kbps in the forward link but only 112 Kbps in the return link (because the Sabreliner docsn't have enough electrical power to afford operating the larger TWTA at it full output power level). The codec recovers the video link after only about 3 sec, including the modem re-acquisition time. The codec requires a channel bit error rate less than 10^{-6}. The video codec will compress/decompress full motion video in real time and format supplemental low rate data, such as BAT GPS reports, into its network data stream. The GI'S reports are relayed from a GPS receiver on the aircraft, via an auxiliary data port on the video codec, to the ACTS Control Facility, which uplinks commands to ACTS to keep the steerable beam pointed at the aircraft throughout the experiments.

E. DAS

A data acquisition systcm (DAS) will record all relevant BAT system parameters to aide in the post-experiment characterization of both the BAT equipment and the communication channel. The DAS records system status information (such as the received signal strength, the filter bandwidths and operating rnodcs of the RF and IF Converters, the Antenna Controller and the Modem, the data received by the modcm, etc.) all while at the same time recording video at rates up to 3 frames per second. Up to eight hours of data can be stored on one 8 mm tape. Such thorough archival recordings allow extensive data analysis at later dates.

V. SUMMARY

Interest continues to increase in reliable voice, data, and video aero-satcom links to improve air traffic control, for airline management, and to meet the growing passenger demand for in-flight communications. These satcom links will provide the connectivity required to extend the communications superhighway envisioned for the future to aircraft in flight. The large amount of frequency spectrum available at K/Ka-band is expected to encourage significant improvements in passenger and cockpit communications - including video teleconferencing and entertainment. It is expected that the spectrum rcqu i red for commercial aero-satcom services will grow significantly beyond that available at L-band, the band now most commonly used.

Anticipating this growth, JPL has begun developing the Broadband Aeronautical Terminal (BAT), an experimental high data rate 20/30 GHz aero-satcom terminal. It will enable high data rate communications from aircraft in flight over ocean and land. The BAT terminal will be used as a digital communications laboratory in the sky to evaluate and characterize aeronautical satcom at K/Ka-band. The system will be demonstrated in both a Lockheed C-141 large cargo jet used as an airborne infrared observatory by NASA Ames Research Center, and also a eight-seat Sabreliner 50 business jet provided by Rockwell Collins. The results of this effort are expected to help shape the future of commercial aero-satcom, building up the capabilities required to extend the communications superhighway envisioned for the future into the airline passenger cabin and cockpit.

VI. ACKNOWLEDGMENTS

The research described in this paper was conducted by the Jet Propulsion Laboratory (JPL), California Institute of Technology, under contract with the National Aeronautics and Space Administration. The antenna system development was contracted by JPL (Contract No. 959832) to EMS Technologies, and the antenna controller development was subcontracted by EMS to CAL Corporation. The aircraft used for the flight experiments have been made available by Rockwell International Corp., Collins Avionics & Communications Division and NASA's Ames Research Center.

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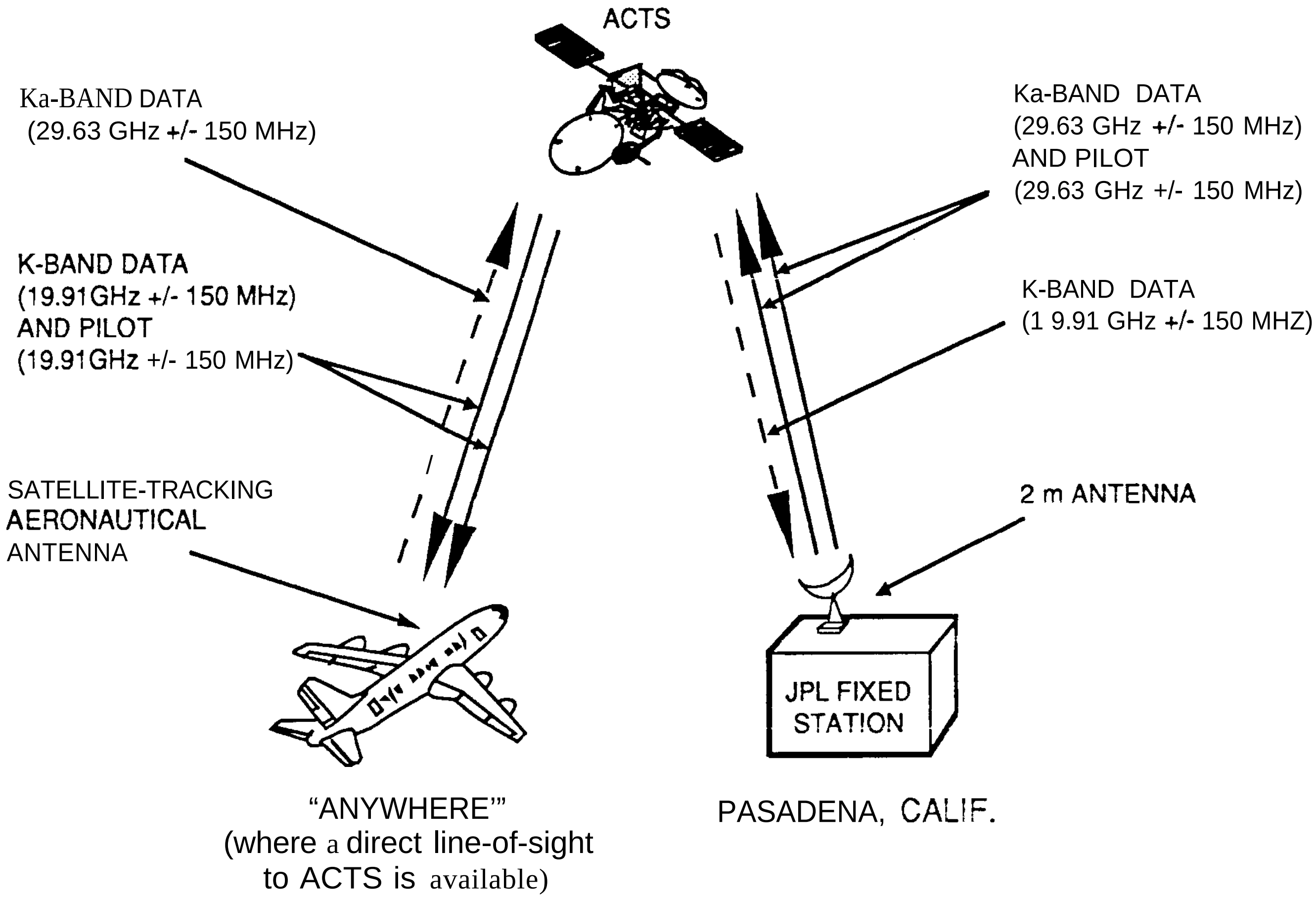


Fig. 1 Satcom System Configuration

ELEVATION ANGLE TO SATELLITE -100°

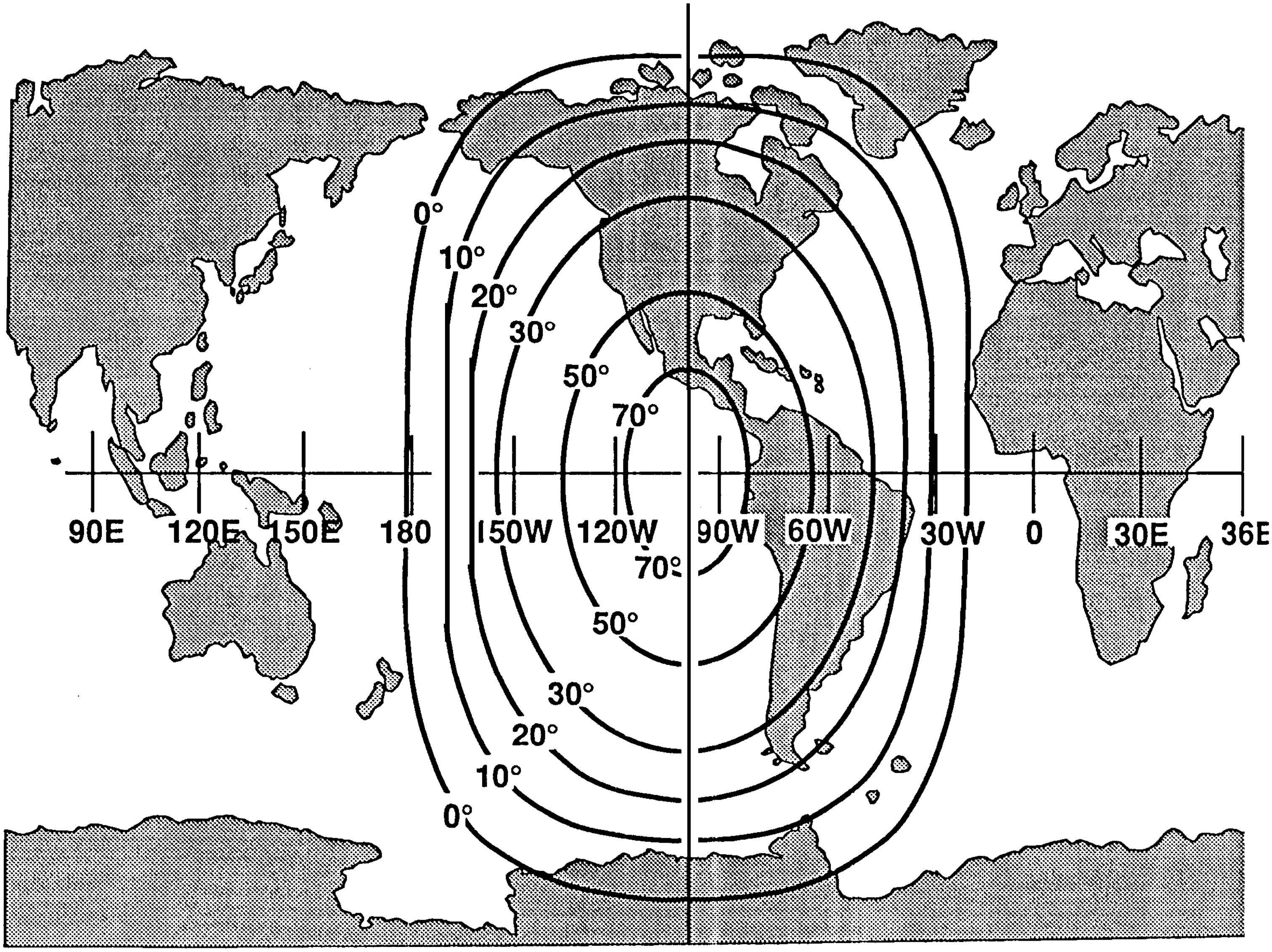


fig 2 ACTS Look Angle

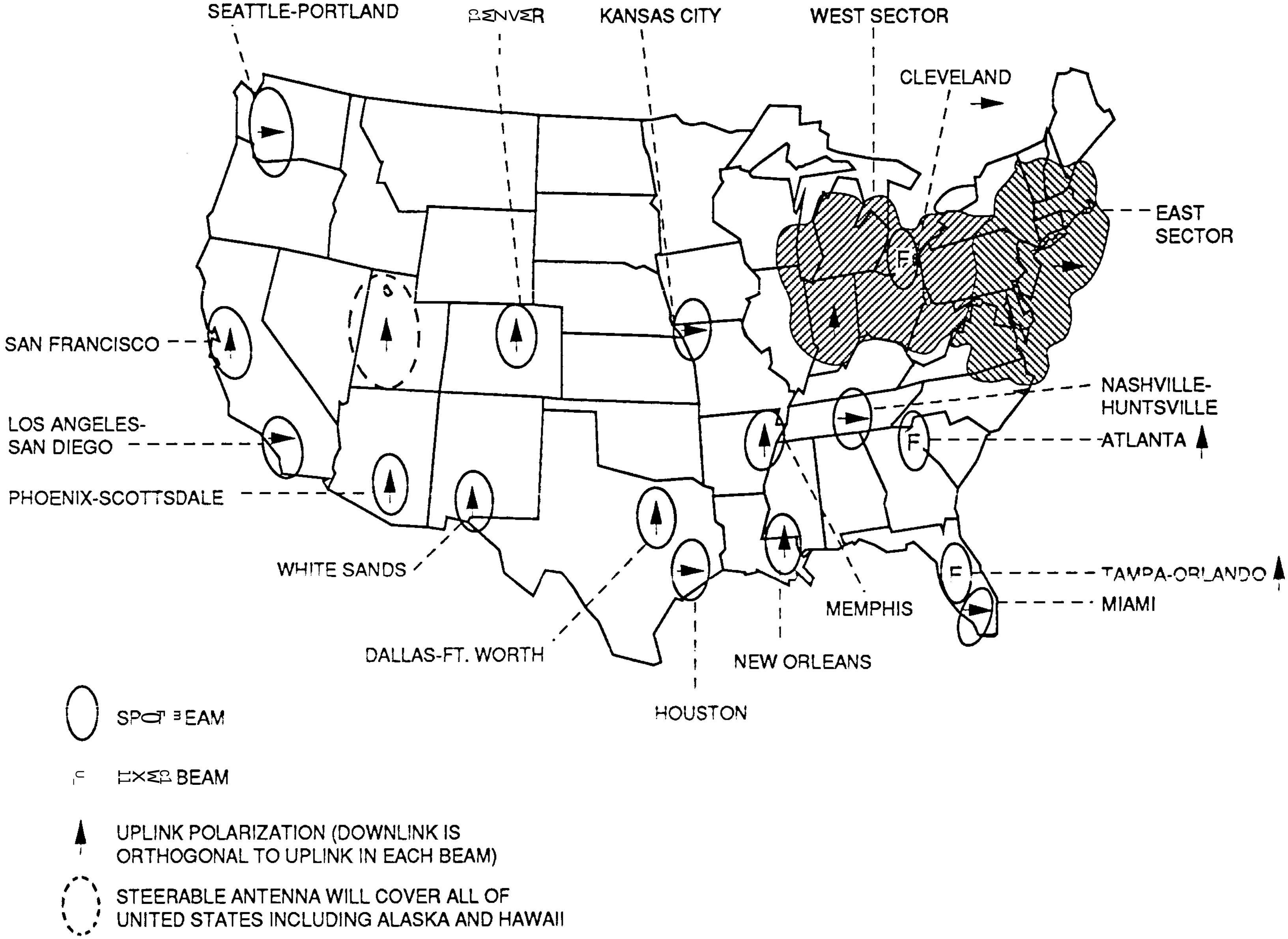


Fig. 3 ACTS Spot Beams

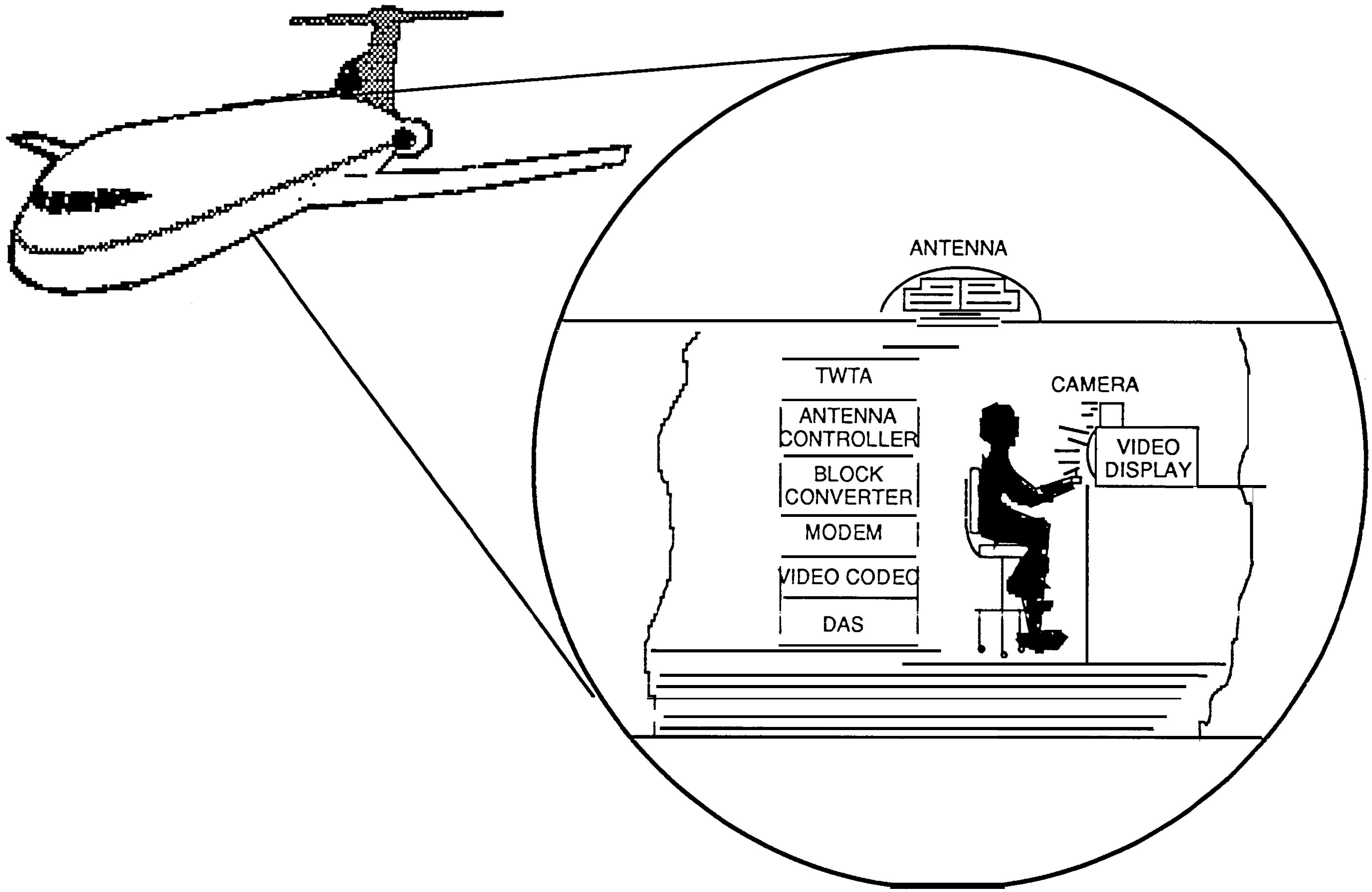


Fig. 4 Aircraft Installation Concept

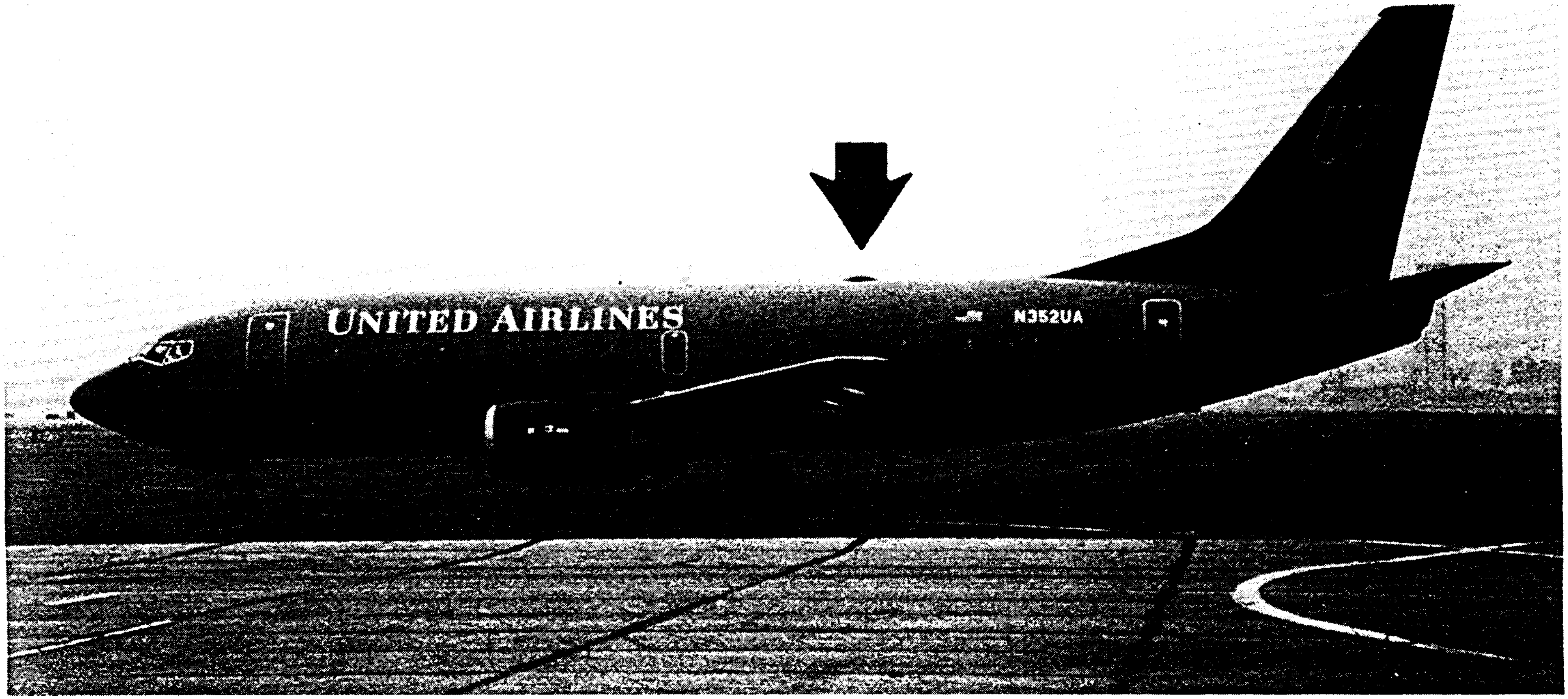


Fig. 5 Scale Perspective of the a on Boeig 737

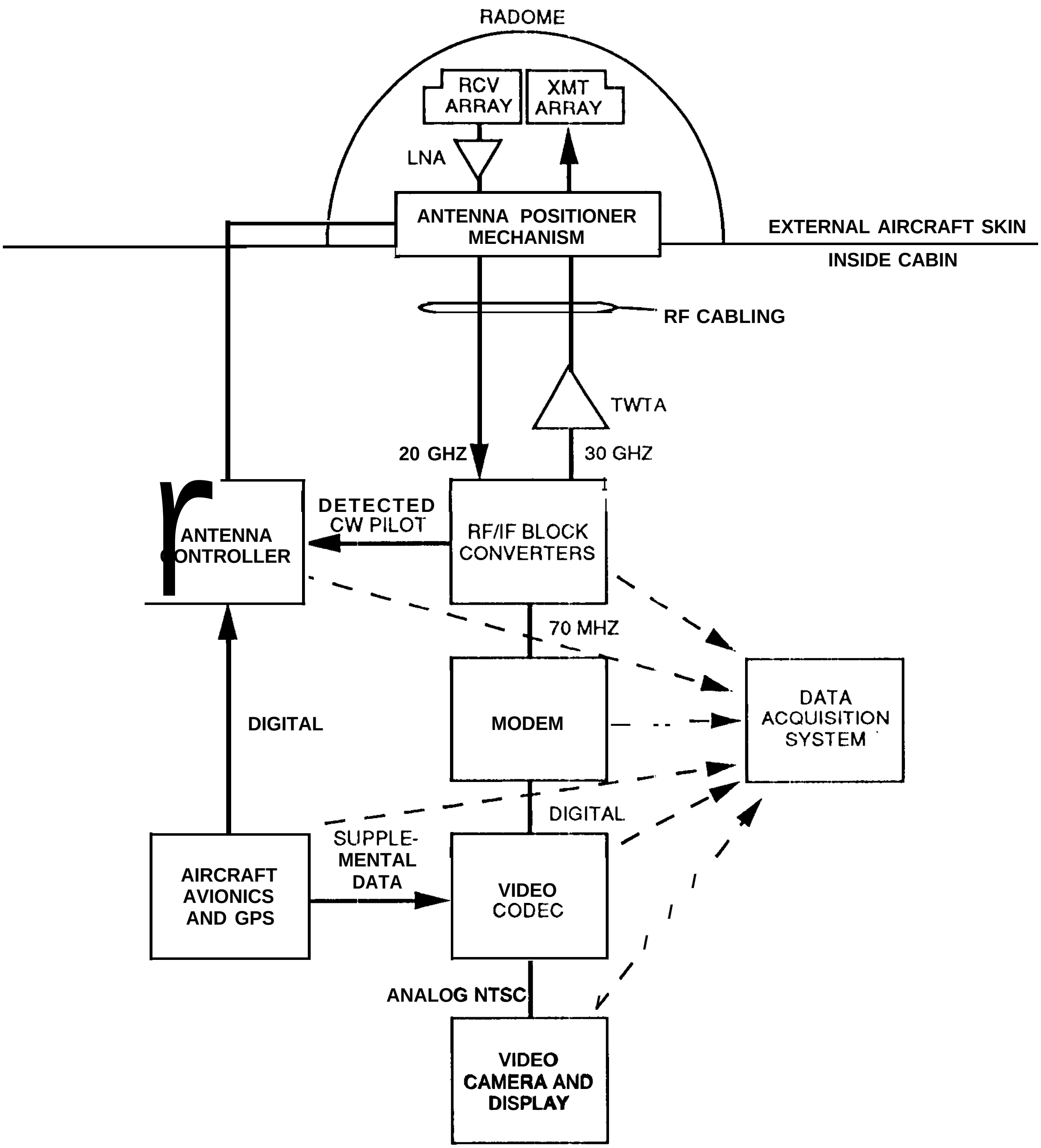


Fig 6. BAT Block Diagram

JPL Aeronautical Antenna System

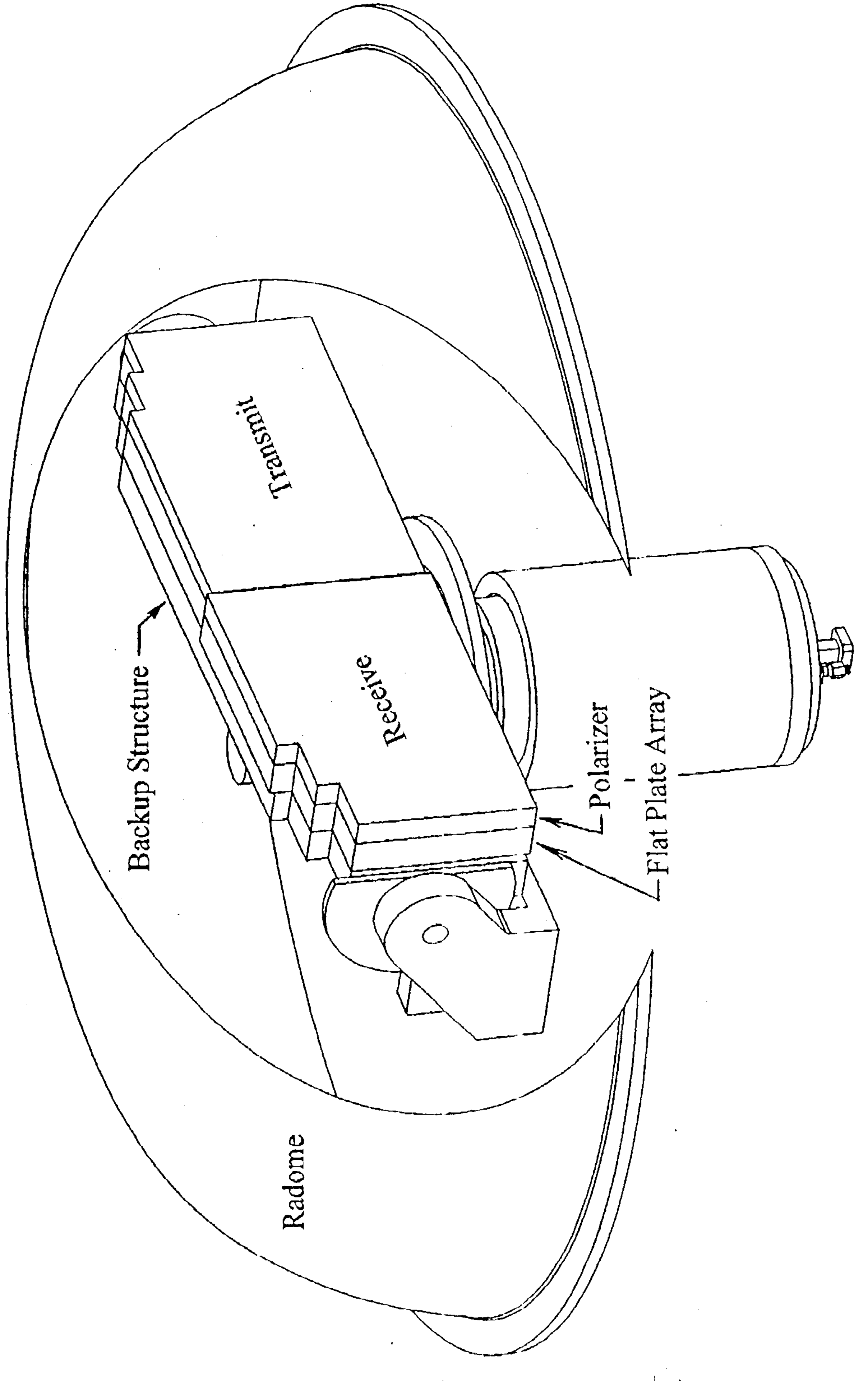
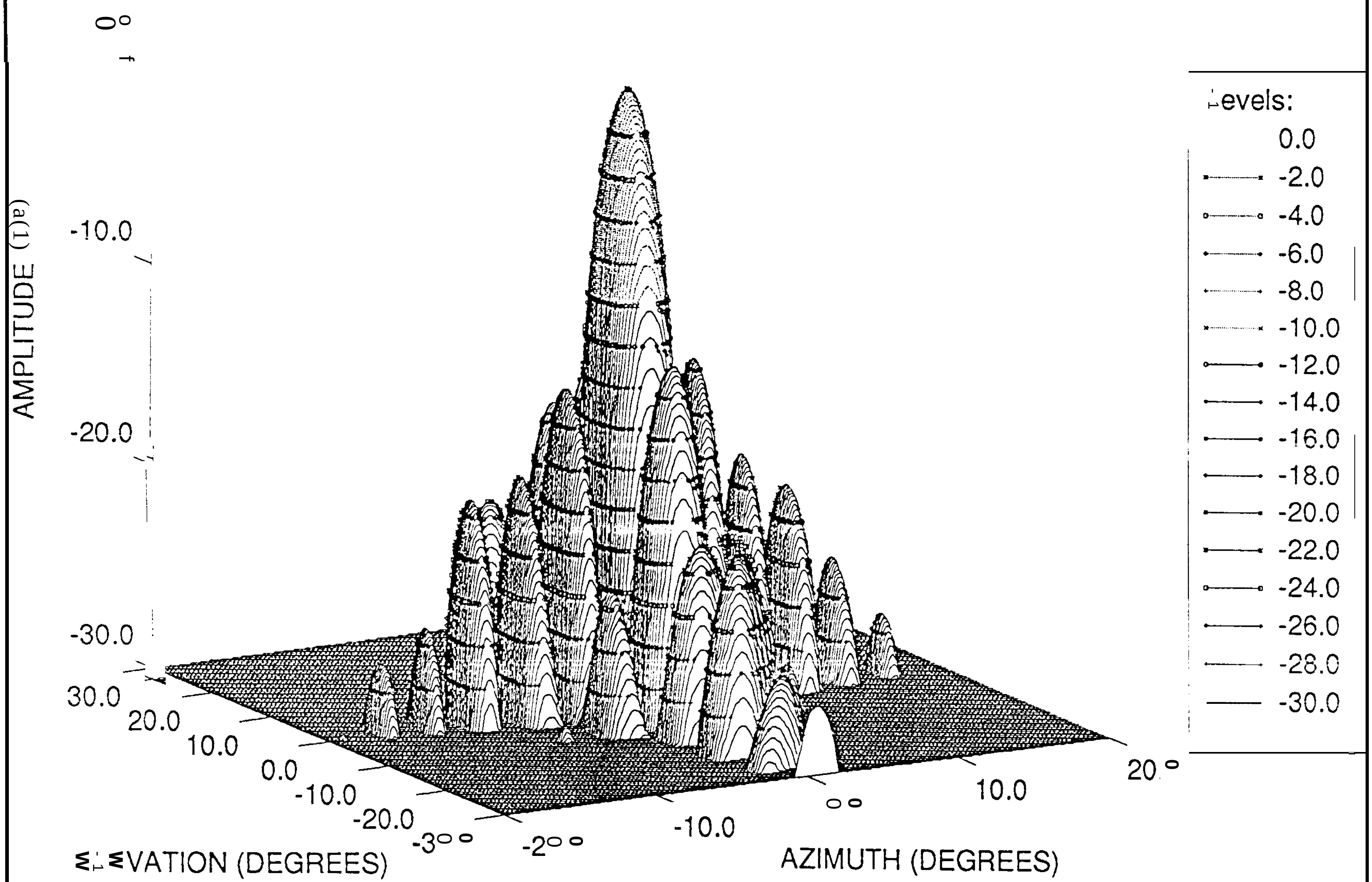


Fig 7: Antenna Sketch

30 GHz TRANSMIT ANTENNA RADIATION PATTERN

(FROM MEASURED NEAR FIELD RANGE DATA 12/23/94)



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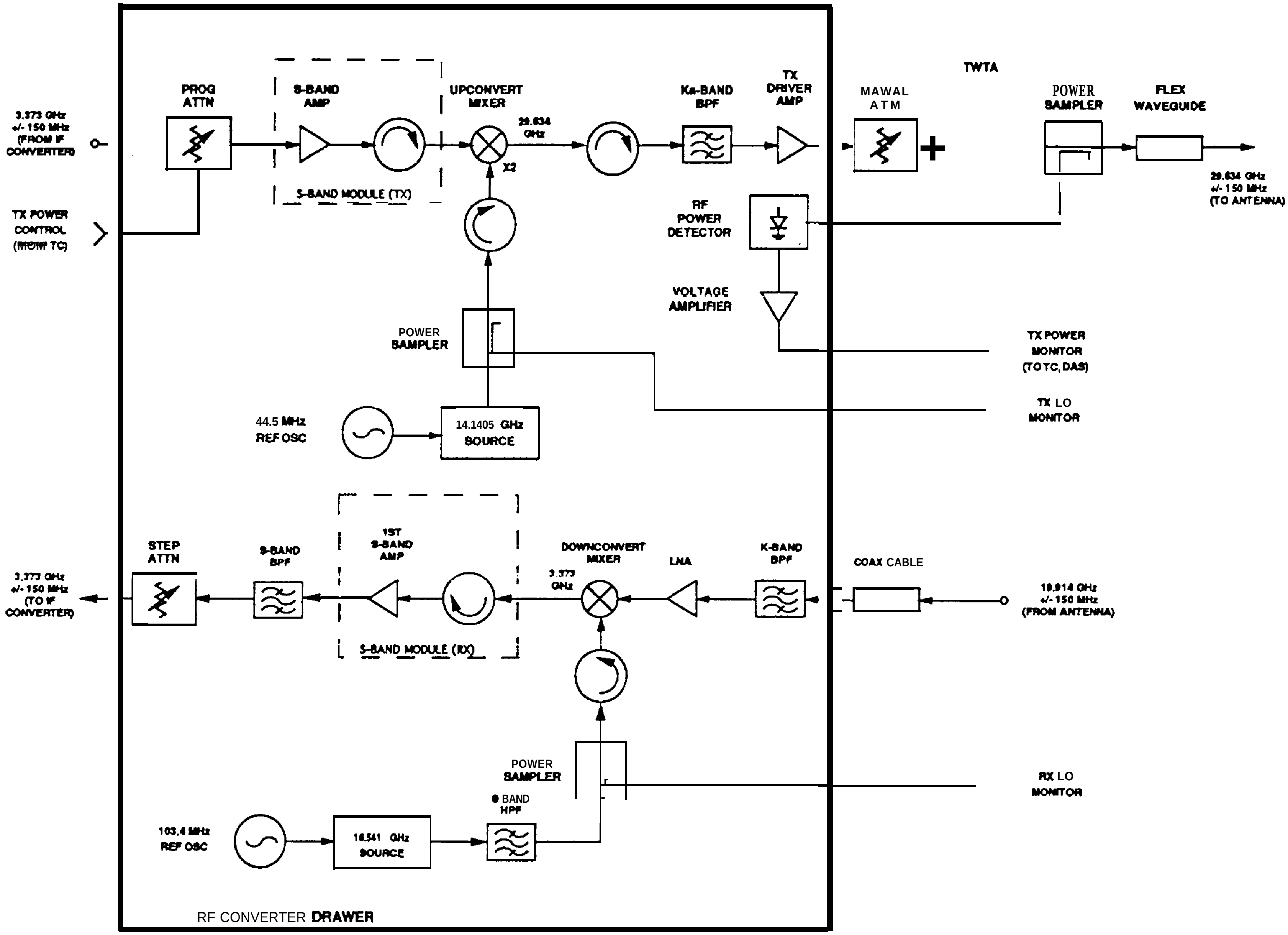
An Electromagnetic Sciences Company

Fig. 8 Transmit Antenna Pattern Measured



9

Figure/X'- RF Converter Block Diagram

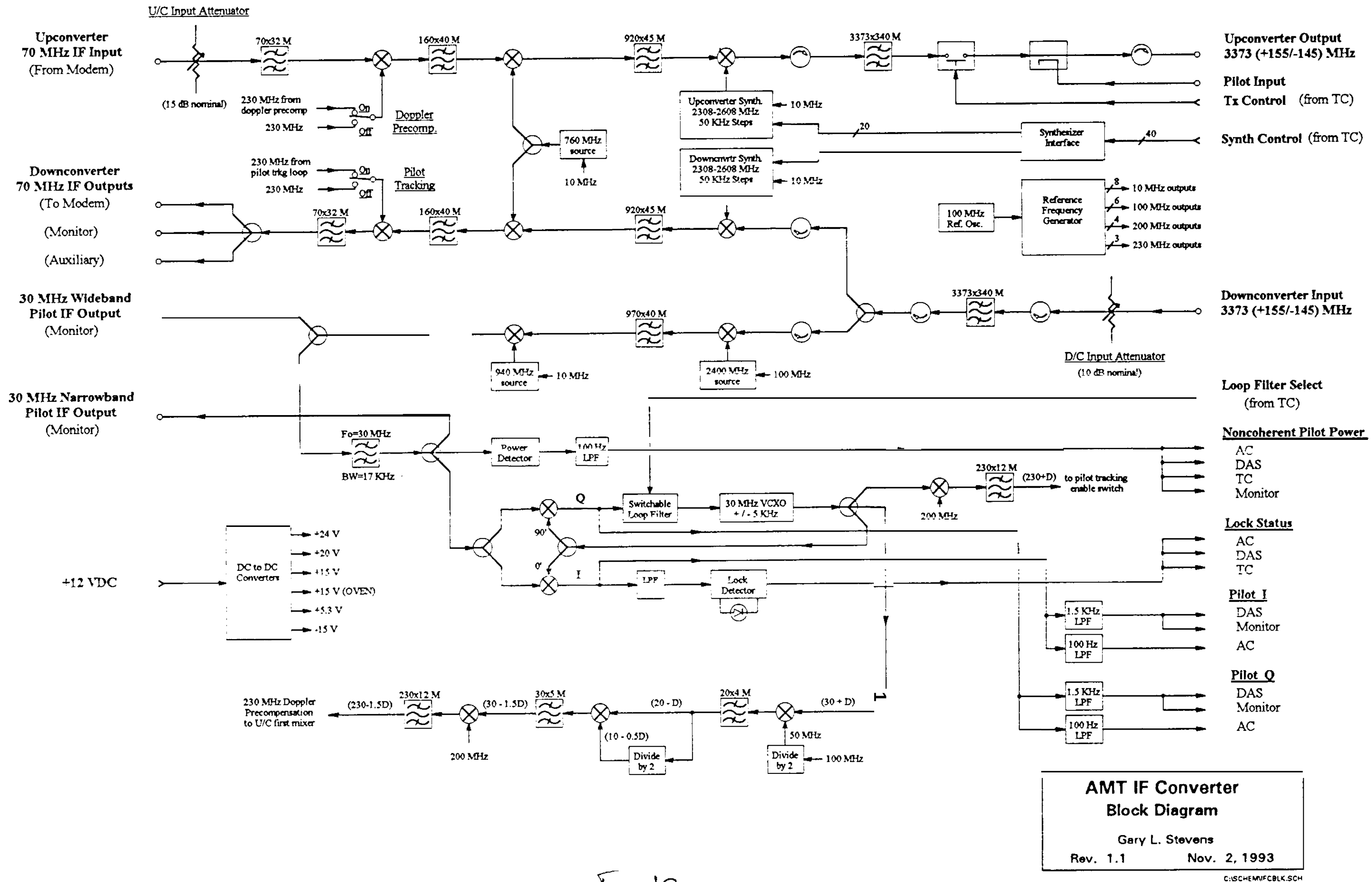

U/C Input Attenuator
Upconverter
70 MHz IF Input
(From Modem)
(15 dB nominal)
70x32 M
160x40 M
920x45 M
3373x340 M
Upconverter Output
3373 (+155/-145) MHz
Pilot Input
Tx Control (from TC)
Synth Control (from TC)
230 MHz from doppler precomp
230 MHz
On
Off
Doppler Precomp.
760 MHz source
10 MHz
Upconverter Synth. 2308-2608 MHz 50 KHz Steps
Downcnvrtr Synth. 2308-2608 MHz 50 KHz Steps
Synthesizer Interface
20
40
Downconverter
70 MHz IF Outputs
(To Modem)
(Monitor)
(Auxiliary)
230 MHz from pilot trkg loop
Pilot Tracking
100 MHz Ref. Osc.
Reference Frequency Generator
10 MHz outputs
100 MHz outputs
200 MHz outputs
230 MHz outputs
30 MHz Wideband
Pilot IF Output
(Monitor)
970x40 M
940 MHz source
2400 MHz source
100 MHz
Downconverter Input
3373 (+155/-145) MHz
D/C Input Attenuator
(10 dB nominal)
30 MHz Narrowband
Pilot IF Output
(Monitor)
Loop Filter Select
(from TC)
Fo=30 MHz
BW=17 KHz
Power Detector
100 Hz LPF
Noncoherent Pilot Power
AC
DAS
TC
Monitor
230x12 M
(230+D)
to pilot tracking enable switch
Q
I
90°
0°
Switchable Loop Filter
30 MHz VCXO +/- 5 KHz
200 MHz
Lock Status
LPF
Lock Detector
+12 VDC
DC to DC Converters
+24 V
+20 V
+15 V
+15 V (OVEN)
+5.3 V
-15 V
Pilot I
1.5 KHz LPF
Pilot Q
1
230 MHz Doppler Precompensation to U/C first mixer
(230-1.5D)
(30 - 1.5D)
30x5 M
(20 - D)
20x4 M
(30 + D)
(10 - 0.5D)
Divide by 2
50 MHz
AMT IF Converter
Block Diagram
Gary L. Stevens
Rev. 1.1 Nov. 2, 1993
C:\SCHEM\IFCBLK.SCH

Fig 10

Forward ([illegible])

	A	B	C	D	E
1					
2		FORWARD LINK (JPL -TO-ACTS-TO-AIRCRAFT)			
3		384 KBPS VIDEO, BER = 1 E-6			
4		BPSK, CONCATENATED CONVOLUTIONAL/REED-SOLOMON CODE			
5		**USING MECHANICALLY** STEERABLE SATELLITE ANTENNA			
6					
7					
8		UPLINK: JPL SUPPLIER-TO-ACTS	DATA SIGNAL.		PILOT SIGNAL
9					
10		TRANSMITTER **PARAMETERS**			
11		TRANSMIT POWER, DBW	16.7		
12		WAVEGUIDE LOSS, DB	-8,5		
13		ANTENNA GAIN, DBi	54.8		
14		AVAILABLE EIRP, DBW	63.0		63.0
15		PERCENTAGE OF EIRP IN DATA SIGNAL, %	91.0		
16		EIRP, DBW	62.6		52.5
17		POINTING LOSS, DB	-0.8		-0.8
18		PATH PARAMETERS			
19		SPACE LOSS, DB	-213.5		-213.5
20		(FREQ., GHZ/MHZ	29.6		29.6
21		ACTUAL RANGE, KM)	38000.0		38000,0
22		ATMOSPHERIC ATTN, DB	-0.4		-0.4
23		RECEIVER PARAMETERS			
24		POLARIZATION LOSS, DB	-0.1		-0,1
25		G/T (EOC), DB/K	17.9		17.9
26		POINTING LOSS, DB	-0.1		-0.1
27		BANDWIDTH, MHZ	900.0		900.0
28		RECV'D C/NO, DB.HZ	94.2		84,1
29		TRANSPONDER SNR IN, DB	4.6		-5.4
30		EFF. LIM. SUPPRESSION, DB **	-0.2		-0,2
31		HARD LIM. EFF. SNR OUT, DB	4.4		-5.6
32					
33		DOWNLINK: ACTS-TO-AIRCRAFT			
34					
35		TRANSMITTER PARAMETERS			
36		STEERABLE BEAM MINIMUM PEAK EIRP	55.7		55.7
37		EIRP, DBW	54.1		44.0
38		POINTING LOSS (EDGE OF BEAM), DB	-0.5		-0.5
39		PATH PARAMETERS			
40		MAX. SPACE LOSS (10° ELEVATION), DB	-211.1		-211.1
41		(FREQ., GHZ	19.9		19.9
42		MAX. RANGE (AT 10° ELEVATION ANGLE), K	42800.0		42800,0
43		ATMOSPHERIC ATTN, DB	-0,5		-0.5
44		RECEIVER PARAMETERS			
45		POL. LOSS: CIRCULAR W/2DB AXIAL RAT., DB	-4.1		-4.1
48		G/T (W/RADOME), DB/K	0.0		0.0
49		POINTING LOSS, DB	-0.5		-0.5
50		DOWNLINK C/NO, DB.HZ	65.9		55.9
51		OVERALL C/NO, DB.HZ	65.9		55.9
52		REQ'D EB/N0 (AWGN--SIMULATION), DB	3.0		
53		MODEM IMPLEMENT. LOSS, DB	1.0		
54		LOSS DUE TO FREQ. OFFSETS/DOP., DB	1.0		
55		REQUIRED EB/NO, DB	5.0		
56		LOSS DUE TO ACTS PHASE NOISE, DB	1.0		
57		DATA RATE, KBPS	384.0		
58		REQ'D EFFECTIVE C/NO, DB.HZ	61.8		
59			....		
60		PERFORMANCE MARGIN, DB	4.1		
61					
62		-			
63		** HERE CASE OF TWO EQUAL SIGNALS IN NOISE (MEASURED)			
64					

table 1

#1

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[illegible]

	A	B	C
1			
2		RETURN LINK (AIRCRAFT-TO-ACTS-TO-JF'L)	
3		384 KBPS VIDEO, BER = 1 E-6	
4		BPSK, CONCATENATED REED-SOLOMON/CONVOLUTIONAL CODE	
5		USING MECHANICALLY STEERABLE SATELLITE ANTENNA	
6			
7		UPLINK: AIRCRAFT-TO-ACTS	DATA SIGNAL
8			
9		TRANSMITTER PARAMETERS	
10		TRANSMIT POWER, DBW	20.0
11		BPF & WG LOSSES, DB	-3.8
12		ANTENNA GAIN (W/RADOME), DBiC	29.0
13		EIRP, DBW (NOMINAL)	45.2
14		POINTING LOSS, DB	-0.5
15		POL. LOSS: CIRC. W/2DB AXIAL RAT., DB	-4,1
16		PATH PARAMETERS	
17		MAX. SPACE LOSS (AT 10° ELEVATION ANGI	-214.6
18		(FREQ., GHZ	29.6
19		RANGE, KM)	42800
20		ATMOSPHERIC ATTN, DB	-0.4
21		RECEIVER PARAMETERS	
22		G/T: STEERABLE BEAM PEAK, DB/K	14.5
23		POINTING LOSS(EDGE OF BEAM), DB	-0.5
24		BANDWIDTH, MHZ	900
25		RECV'D C/NO, DB.HZ	68.3
26		TRANSPONDER SNR IN, DB	-21.3
27		LIMITER SUPPRESSION	0.0
28		TRANSPONDER SNR OUT, DB	-21.3
29		————	
30	DOWNLINK: ACTS-TO-JPL		
31		-	
32	TRANSMITTER PARAMETERS		
33		EIRP (EOC), DBW	41.1
34		POINTING LOSS, DB	-0.2
35	PATH PARAMETERS		
36		SPACE LOSS, DB	-210.0
37		(FREQ., GHZ	19.9
38		RANGE, KM)	38000
39		ATMOSPHERIC ATTN, DB	-0,5
40	RECEIVER PARAMETERS		
41		POLARIZATION LOSS, DB	-0.1
42		G/T, DB/K	25.7
43		POINTING LOSS. DB	-0.5
44		DOWNLINK C/NO, DB.HZ	84.1
45		OVERALL C/NO, DB.HZ	68.2
46		REQ'D EB/NO (AWGN--SIMULATION), DB	3.0
47		MODEM IMPLEMENT. LOSS, DB	1.0
48		LOSS DUE TO FREQ. OFFSETS/DOP.,DB	1.0
49		REQUIRED EB/No, DB	5.0
50		LOSS DUE TO ACTS PHASE NOISE,DB	1.0
51		DATA RATE, KBPS	384
52		REQ'D EFFECTIVE C/NO, DB.HZ	61.8
53			....
54		HARDWARE PERFORMANCE MARGIN. DB	6.3

table 2

#2

12/1/94

RETURN LINK **(AIRCRAFT-TO-ACTS-TO-JPL)**
192 ~~384~~ KBPS VIDEO, BER = 1 E-6
BPSK, CONCATENATED REED-SOLOMON/CONVOLUTIONAL CODE
USING MECHANICALLY STEERABLE SATELLITE ANTENNA

B	C
UPLINK: AIRCRAFT-TO-ACTS	DATA SIGNAL
TRANSMITTER PARAMETERS	
TRANSMIT POWER, DBW	16.0
BPF & WG LOSSES, DB	-3.8
ANTENNA GAIN (W/RADOME), DBIC	29.0
EIRP, DBW (NOMINAL.)	41.2
POINTING LOSS, DB	-0.5
POL. LOSS: CIRC. W/2DB AXIAL RAT., DB	-4.1
PATH PARAMETERS	
MAX. SPACE LOSS (AT 10° ELEVATION ANGI	-214.6
(FREQ., GHZ	29.6
RANGE, KM)	42800
ATMOSPHERIC ATTN, DB	-0.4
RECEIVER PARAMETERS	
G/T: STEERABLE BEAM PEAK, DB/K	14.5
POINTING LOSS(EDGE OF BEAM), DB	-0.5
BANDWIDTH, MHZ	900
RECV'D C/NO, DB.HZ	64.3
TRANSPONDER SNR IN, DB	-25.3
LIMITER SUPPRESSION	0.0
TRANSPONDER SNR OUT, DB	-25.3
DOWNLINK: ACTS-TO-JPL	
TRANSMITTER PARAMETERS	
EIRP (EOC), DBW	37.1
POINTING LOSS, DB	-0.2
PATH PARAMETERS	
SPACE LOSS, DB	-210.0
(FREQ., GHZ	19.9
RANGE, KM)	38000
ATMOSPHERIC ATTN, DB	-0.5
RECEIVER PARAMETERS	
POLARIZATION LOSS, DB	-0.1
G/T, DB/K	25.7
POINTING LOSS, DB	-0,5
DOWNLINK C/NO, DB.HZ	80.1
OVERALL C/NO, DB.HZ	64.2
REQ'D EB/N0 (AWGN--SIMULATION), DB	3.0
MODEM IMPLEMENT. LOSS, DB	1.0
LOSS DUE TO FREQ. OFFSETS/DOP., DB	1.0
REQUIRED EB/No, DB	5.0
LOSS DUE TO ACTS PHASE NOISE, DB	1.0
DATA RATE, KBPS	192
REQ'D EFFECTIVE C/NO, DB.HZ	58.8
HARDWARE PERFORMANCE MARGIN, DB	5.3

table 3

#3

12/1/94